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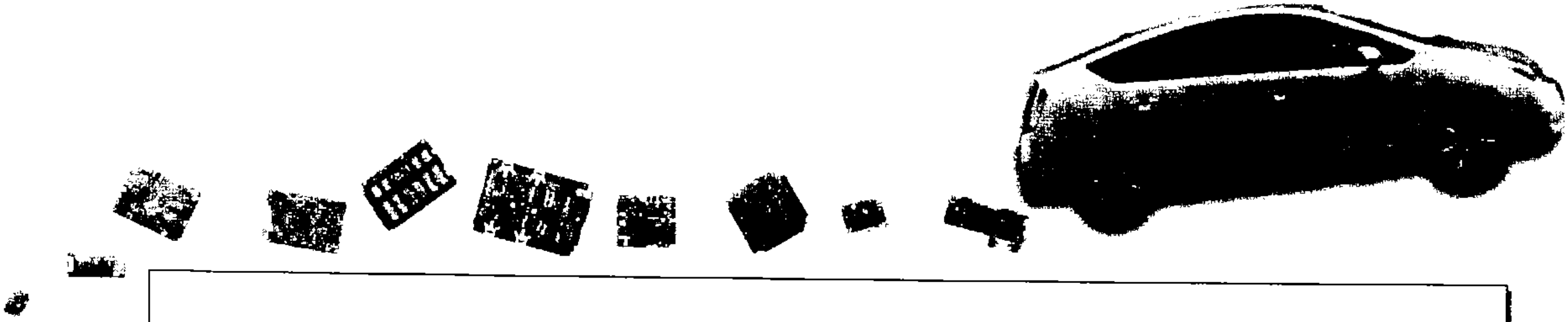


Toyota Prius Teardown:

A sampling of Electronics Modules from the world's most popular Hybrid Vehicle

David Carey / dcarey@teardown.com

This material derived from the Toyota Prius teardown performed at CMP's 2007 Embedded Systems Conference in San Jose (April 2-6)

Portelligent Summary: Toyota Prius Teardown

A Car?

At the recent Silicon Valley Embedded Systems Conference (ESC, April 2-6, 2007) we spent some time taking apart and analyzing the Toyota Prius. Yes, a car! CMP Media, EETimes' parent company and sponsor of ESC decided to buy a brand-new loaded Prius – perhaps the world's best-selling hybrid vehicle – and summarily render it useless as the second installment of "live teardowns" as part of the ESC program. Working with Al Steier of Munro and Assoc. ([illegible]), Portelligent participated in a large-scale teardown to see what makes the Prius tick and better understand how its electronic systems were implemented.

While much of the content here has been published throughout various parts of CMP's media outlets – EETimes, Techonline.com, AutomotiveDesignLine.com, and others – we wanted to summarize the findings in one place for Portelligent clients as an interest piece. A EETimes/Techonline "Under The Hood" Special Supplement, slated for publication May 14th, will also cover more details on the hybrid car with further contributions from Al Steier on the overall Prius design.

There are a number of cases where part identity was uncertain and much of the operational description is speculative based on inspection, component context, and overall system operation. As always, we welcome any comments and/or corrections on the materials presented.

A few pieces out of many....

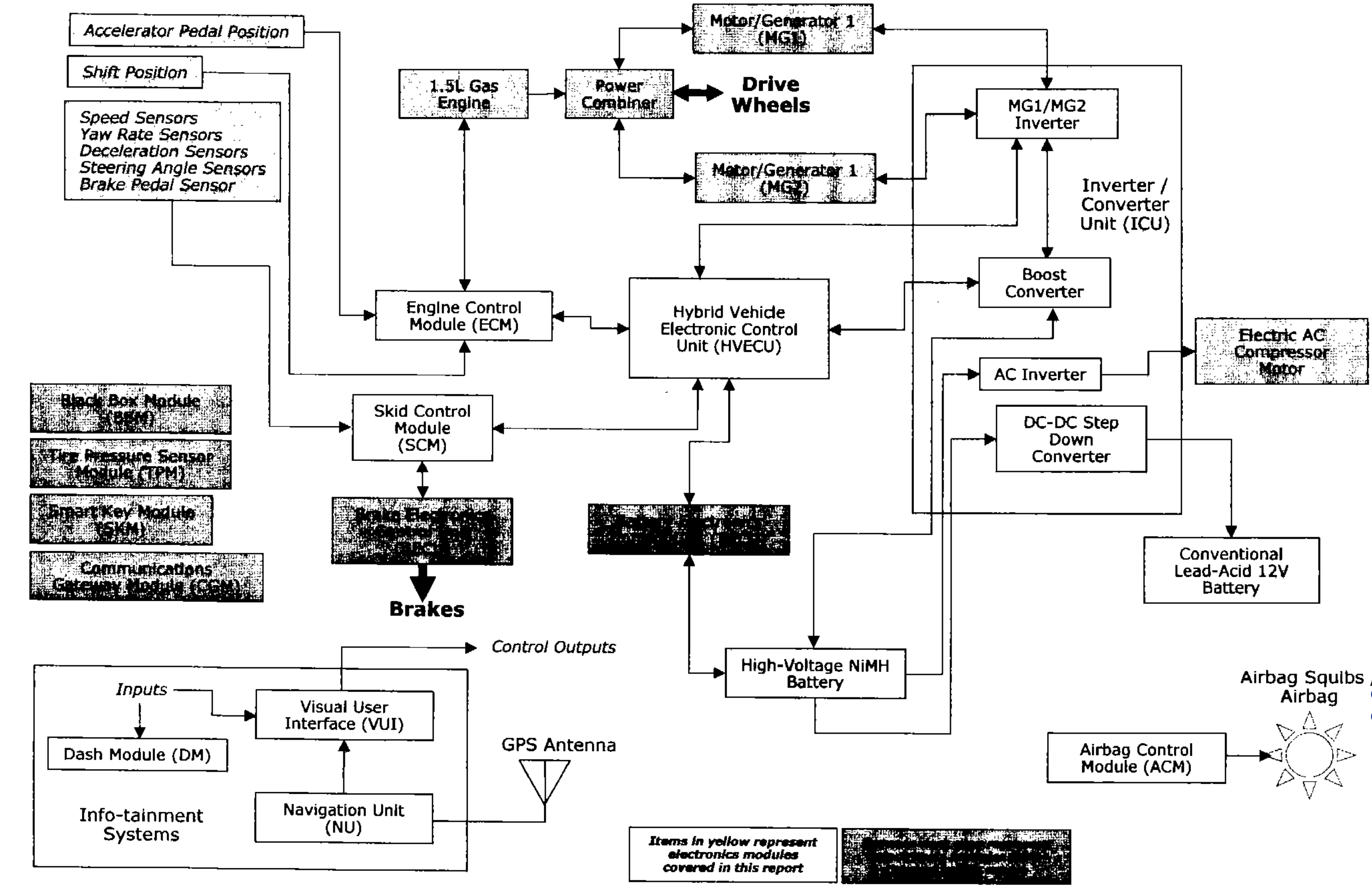
The electronics modules covered here represent just some of the overall Prius electrical design. The major elements of drive train control, safety systems, energy conversion, and info-tainment are reviewed here (see items in yellow on the block diagram following this page) but there is still more to learn. Nevertheless, some top-level conclusions became pretty clear.

First and foremost, the Toyota Prius is a fantastic piece of engineering designed to reduce the financial burden at the pump and to recover energy efficiently. By combining a small gas engine with an electric drive train and regenerative braking, a quite-loved design has been brought to consumers looking to lower their 'carbon footprint' just a bit.

From a technical perspective we found that cautious design is the engineering principle in force, particularly for those subsystems whose role is critical to vehicle operation and safety. While component selections, electronic packaging, and device complexity all became more state-of-the-art as modules for info-tainment were opened up, what's known to work (including 10 year old microprocessor designs) gets a long lifetime in the Toyota design environment. Embedded memory likewise is preferred for control systems and discrete memory packages appeared in the touch screen interface and navigation modules alone.

Lastly, the very distributed nature of automotive electronics was brought into stark relief by the teardown effort. Dozens of microprocessors are sprinkled wherever the local needs of electronics demand, communicating over several different busses, and co-operating to affect vehicle control, power train management, user interface, and safety functions. My flawed notion of a more centralized control system in cars has now been thoroughly dispelled.

Portelligent Summary: Toyota Prius Block Diagram



Portelligent Summary: Engine/Motor Control

Toyota's Prius in many respects can be considered to have two engine controllers, one for the traditional 1.5L gasoline engine (ECM) and another for the electric motors used to alternatively power the car (HVECU).

Starting with the petrol-powered side of the equation, the ECM must constantly monitor a number of input sensors to assess the state of the engine and its own primary inputs of fuel, air, and fire. Airflow monitoring occurs by way of an optical chopper sensor whose output frequency is proportional to flow rate. An engineered vortex in the intake plenum creates a wake in which a mirrored vane flutters faster or slower depending on airflow, with the vane forming the mirrored reflector of the chopper. An oxygen sensor which monitors for proper air-fuel mixture is used as the input to detect either rich or lean conditions. Crankshaft and camshaft position, vehicle speed, throttle position, engine/intake-air temperature, knock detect, and other engine conditions are among the additional inputs to the ECM.

Output functions of the ECM are primarily used to affect airflow, fuel-injector delivery, intake valve closure angle, and spark timing as a means to close the control loop in the engine and maintain optimal power delivery and minimize emissions. Injector solenoids are pulse-width modulated to control fuel delivery volume and timing, and separately the spark timing is driven to precisely control detonation. Ignition timing is retarded when the piezoelectric knock sensor input indicates pre-detonation. Further efficiency refinement is achieved by extending the intake valve opening (Atkinson Cycle operation) to effectively reduce displacement since the intake valves remain open partway into the compression stroke.

The HVECU manages control of the electrical drive plant. Heavy communication with the ECM used to coordinate the relative contributions of gas power, electric power, or in many cases the combined efforts of the two systems to provide propulsion. As with the ECM, the HVECU has its own set of inputs and outputs to implement a closed loop control system. Much of the HVECU interaction occurs with the two motor/generator units of the Prius (MG1 and MG2) which provide drive or recovered energy during regenerative braking. Here motor speed/position sensors in the MG1 and MG2 units are used as inputs to the HVECU along with shift level position, and even accelerator pedal position.

The Inverter/Converter Unit (ICU) which handles all of the electrical conversion in the system is covered in a separate section of this report but as would be expected, the HVECU is also instrumental in the control of the ICU, whose operation is responsible for energy delivery/recovery to/from MG1 and MG2.

Both ECM and HVECU share common attributes in their implementation.

Although housed inside the cabin of the car, physical construction of both ECM and HVECU reflects an emphasis on reliability with sturdy housings and protective coatings on the entire circuit board assemblies. The Quad Flat Pack (QFP) and other peripheral-leaded IC device packaging used throughout both engine control boards provides for a long record of reliability. Without an emphasis on miniaturization, the history of "what we know works" seems to drive technical choices.

The two engine control modules use a common Toyota private-labeled Toyota / NEC #uPD70F3155 32-bit Microprocessor as the primary source of computing power. Neither ECM nor HVECU contain discrete memory components and the NEC processor die contains both the volatile working memory and non-volatile ROM used to store control code.

The balance of components on the ECM are custom to the module manufacturer Denso, and most appear visually to implement the mixed-signal interfaces present at the inputs and outputs where sensors must be digitized and actuators driven.

A more complex set of ICs support the NEC microprocessor on the HVECU. Two Mitsubishi 16-bit microprocessors are each paired with a Tamagawa #AU6802N1 angle encoder and a custom Toshiba analog device, perhaps corresponding to the MG1 and MG2 input interfaces. Another pair of Mitsubishi 16-bit controllers in the HVECU probably manages communications with the ICU, ECM, and Skid Control.

Custom Denso and Toyota chips found in the motor and engine control modules speak to the unique devices needed for mixed-signal interface where no merchant-market devices are available. It's also worth noting that the Mitsubishi controllers have die-level copyrights dating back as far as 1995, further evidence of the measured pace of change and conservative design practices found in the mission-critical elements of automotive electronics.

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Engine Control Module (ECM)

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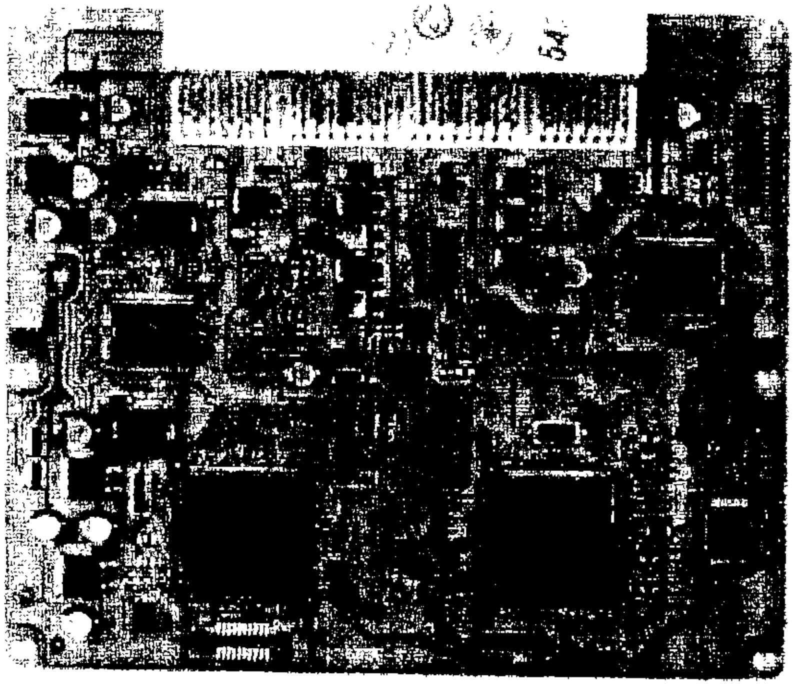
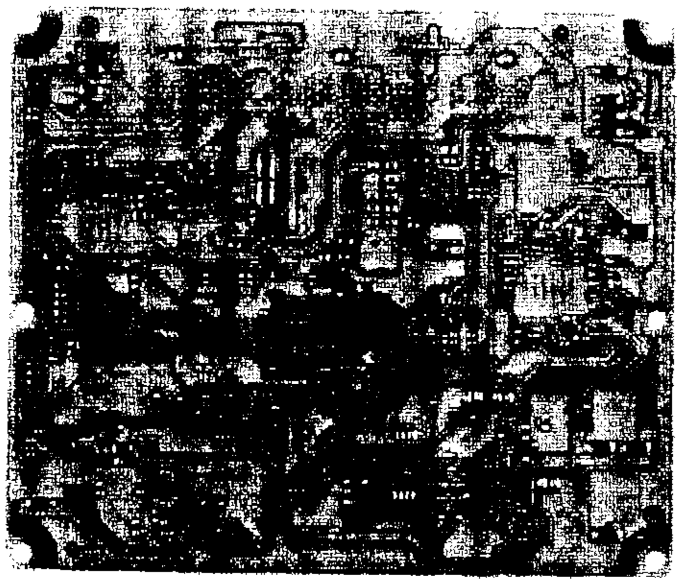
Toyota Prius: *Engine Control Module (ECM)*





ECM components primarily on one side

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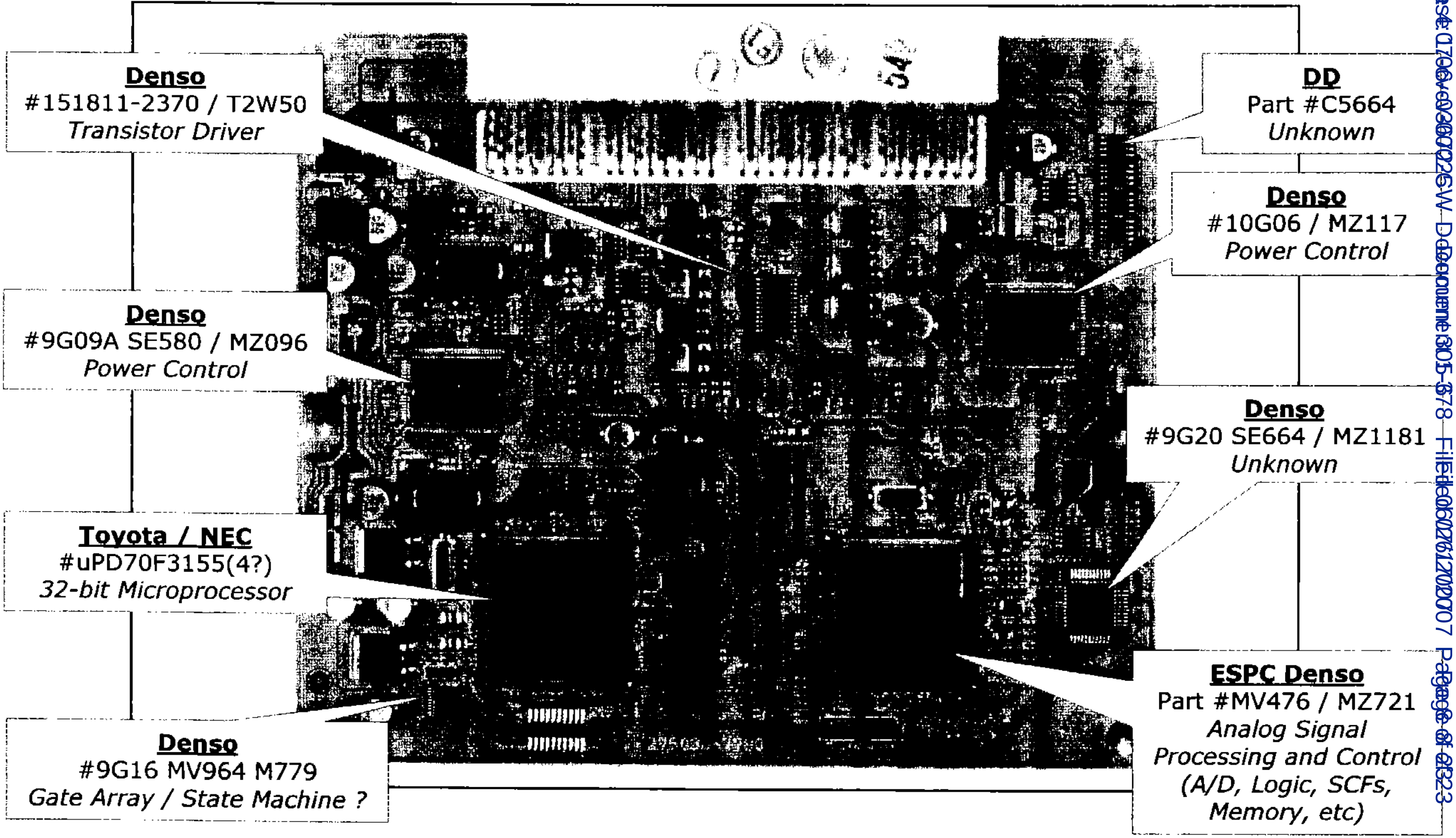
Toyota Prius:
Engine Control Module (ECM)



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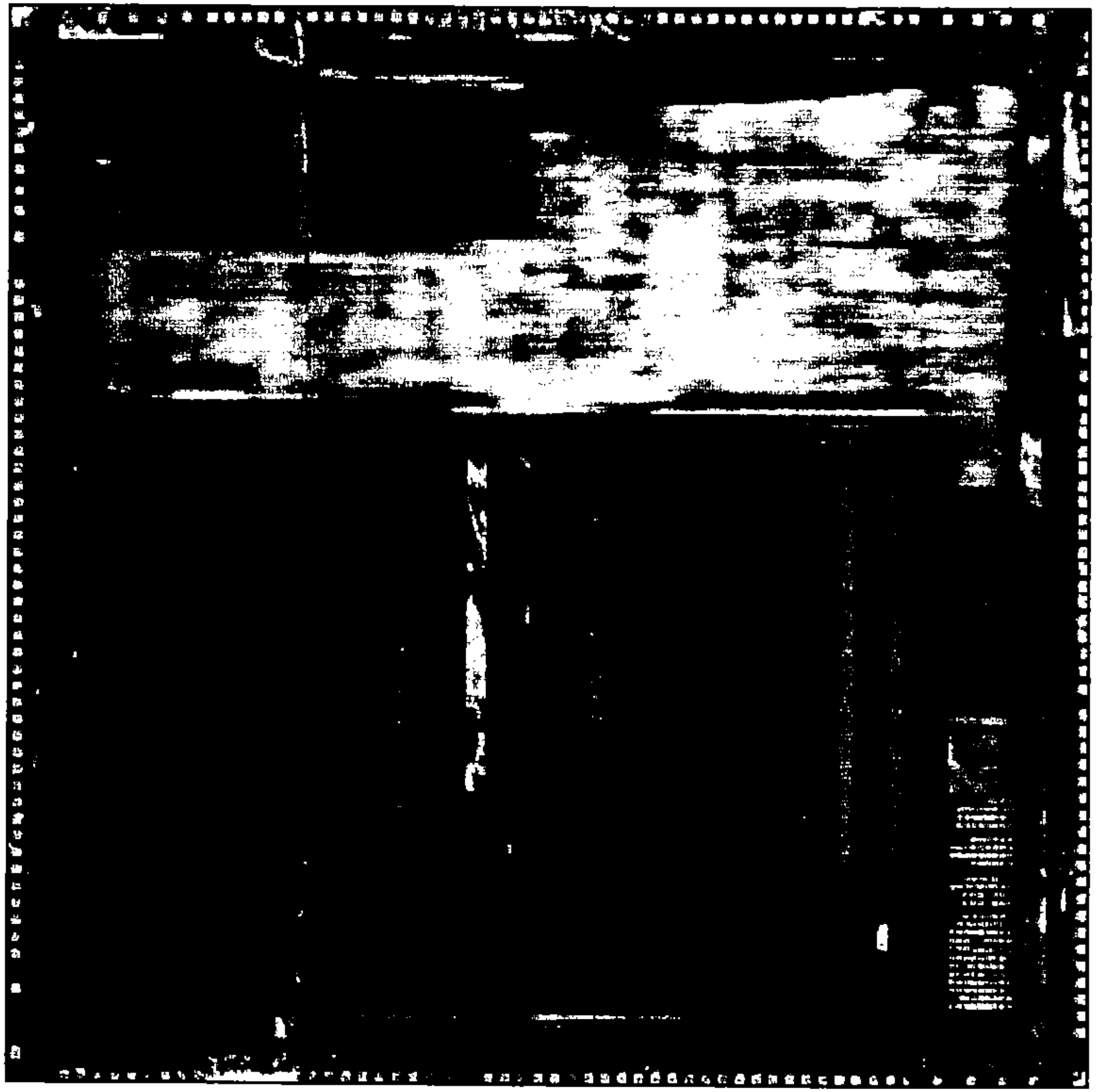
Toyota Prius:
ECM Main Controller



Toyota / NEC
#uPD70F3155(4?)
32-bit Microprocessor

Hybrid Vehicle Electronics Control Unit (HVECU)

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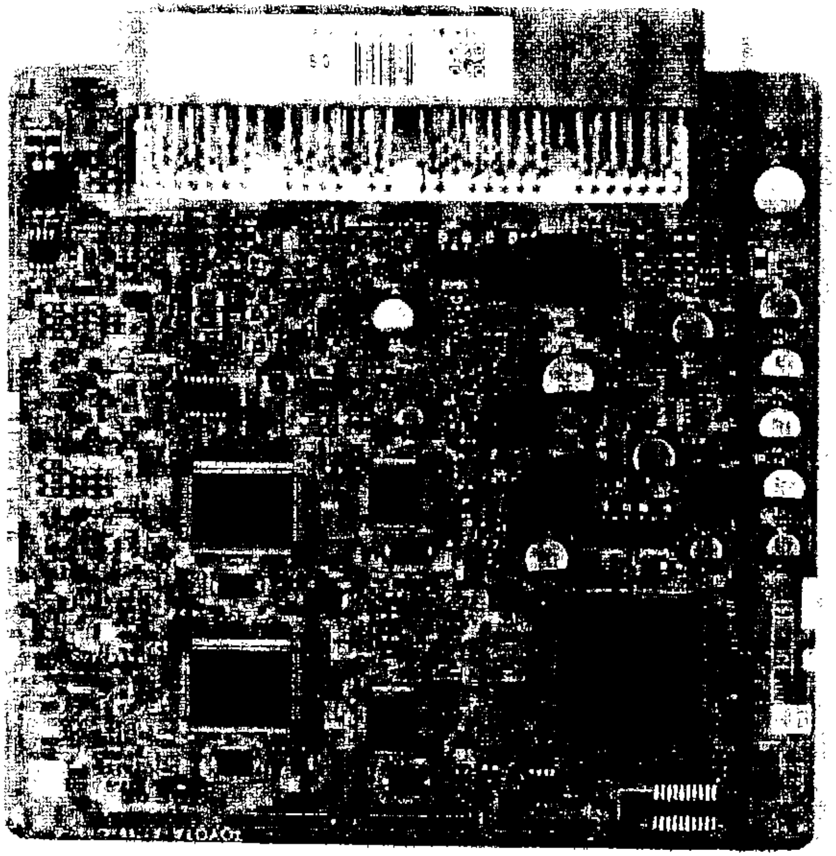
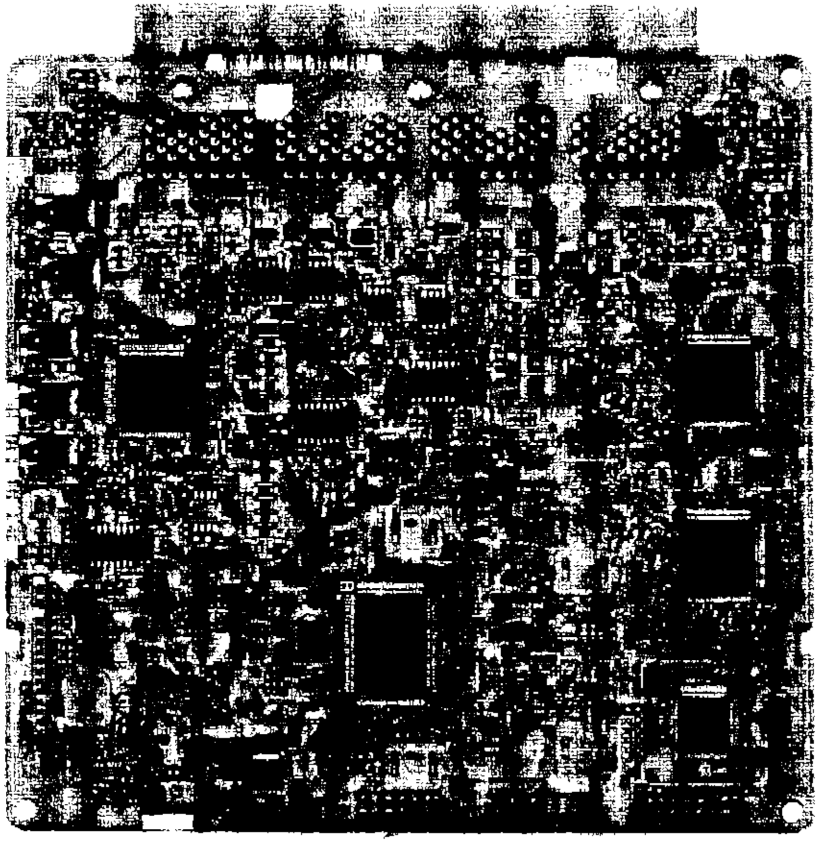
Toyota Prius:
HVECU – Side 1/2





HVECU Control Board populated on both sides.

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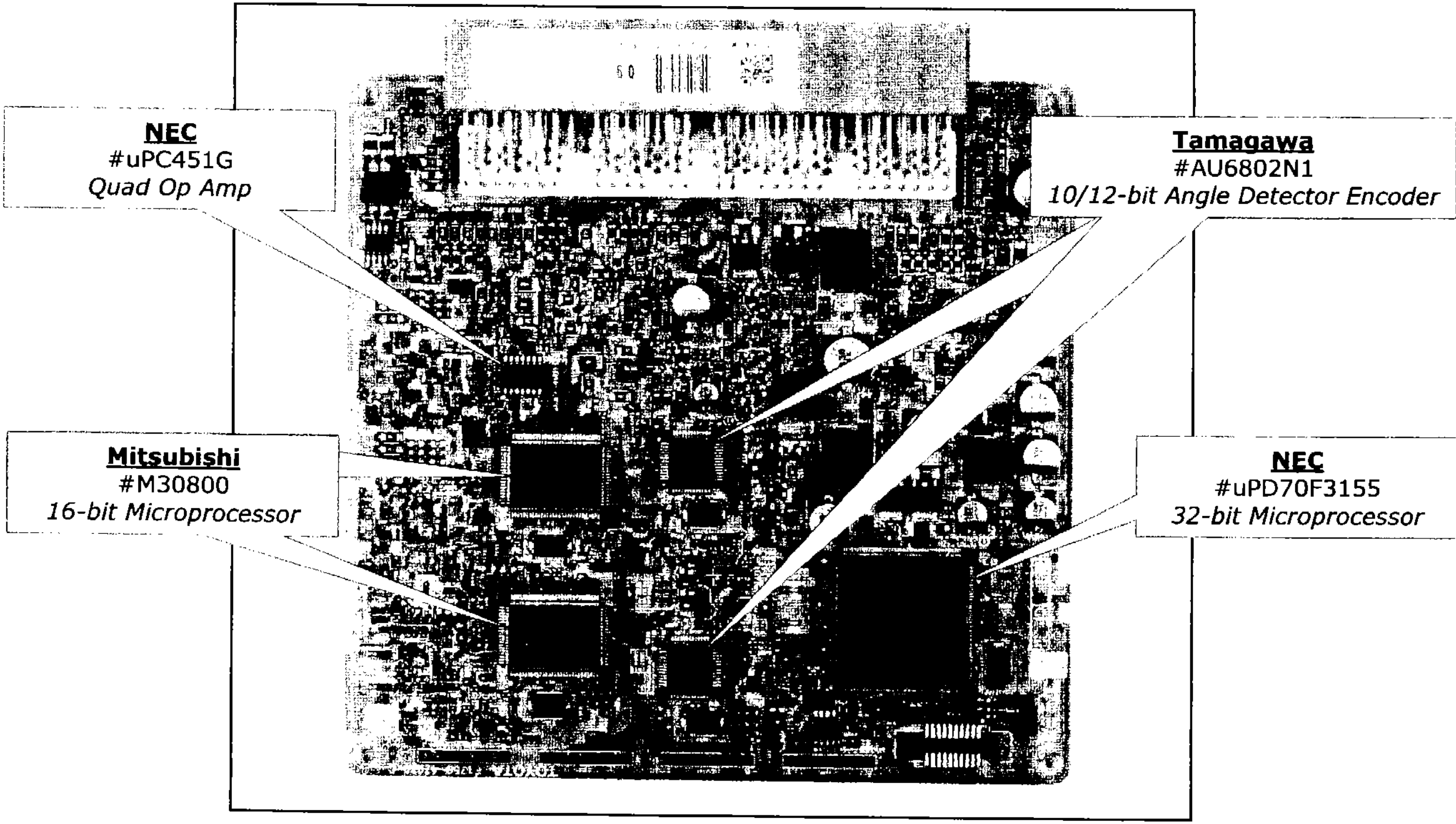
Toyota Prius:
HVECU – Side 1



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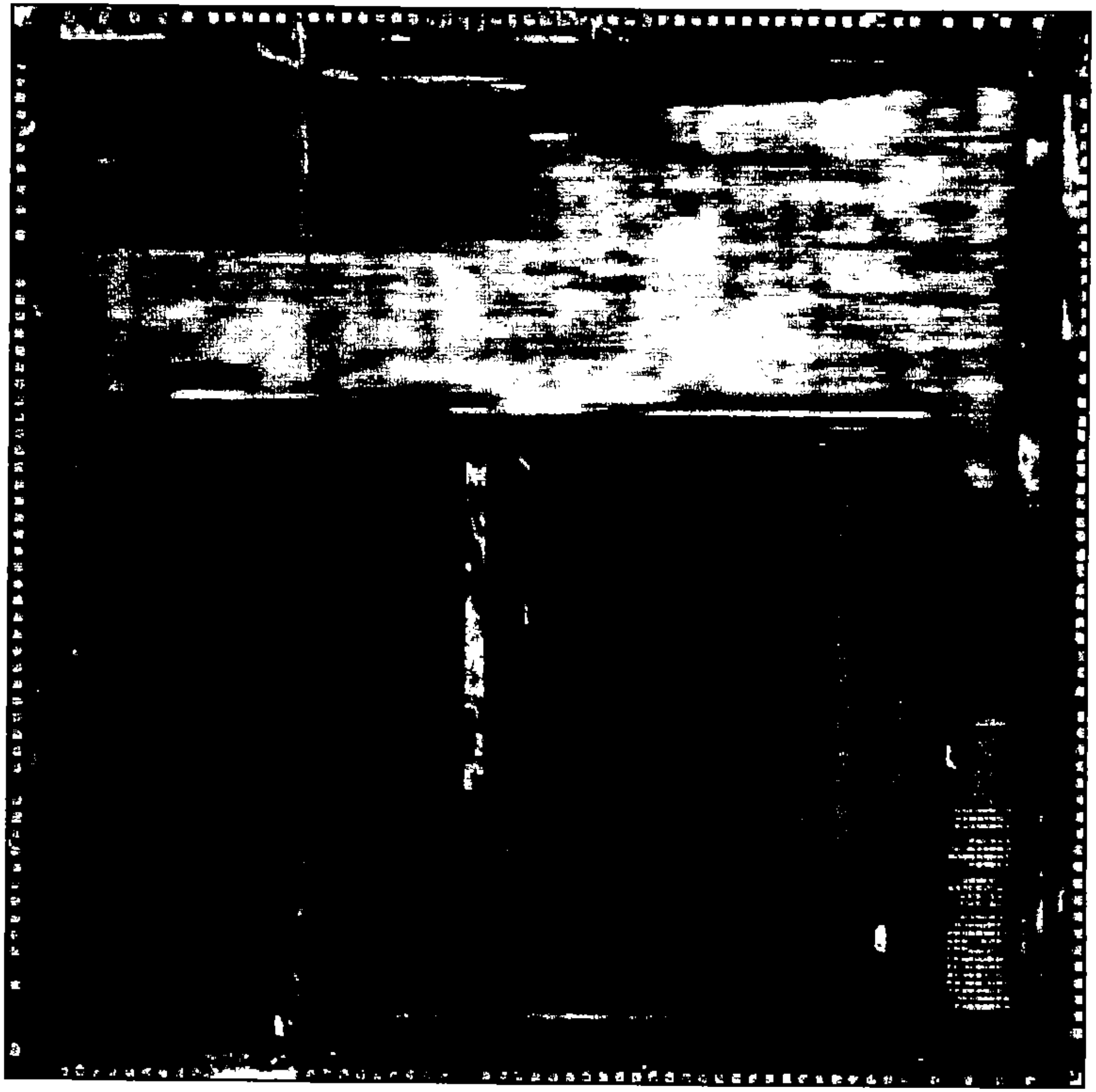
Toyota Prius:
HVECU Main Controller

Toyota / NEC
#uPD70F3155(4?)
32-bit Microprocessor



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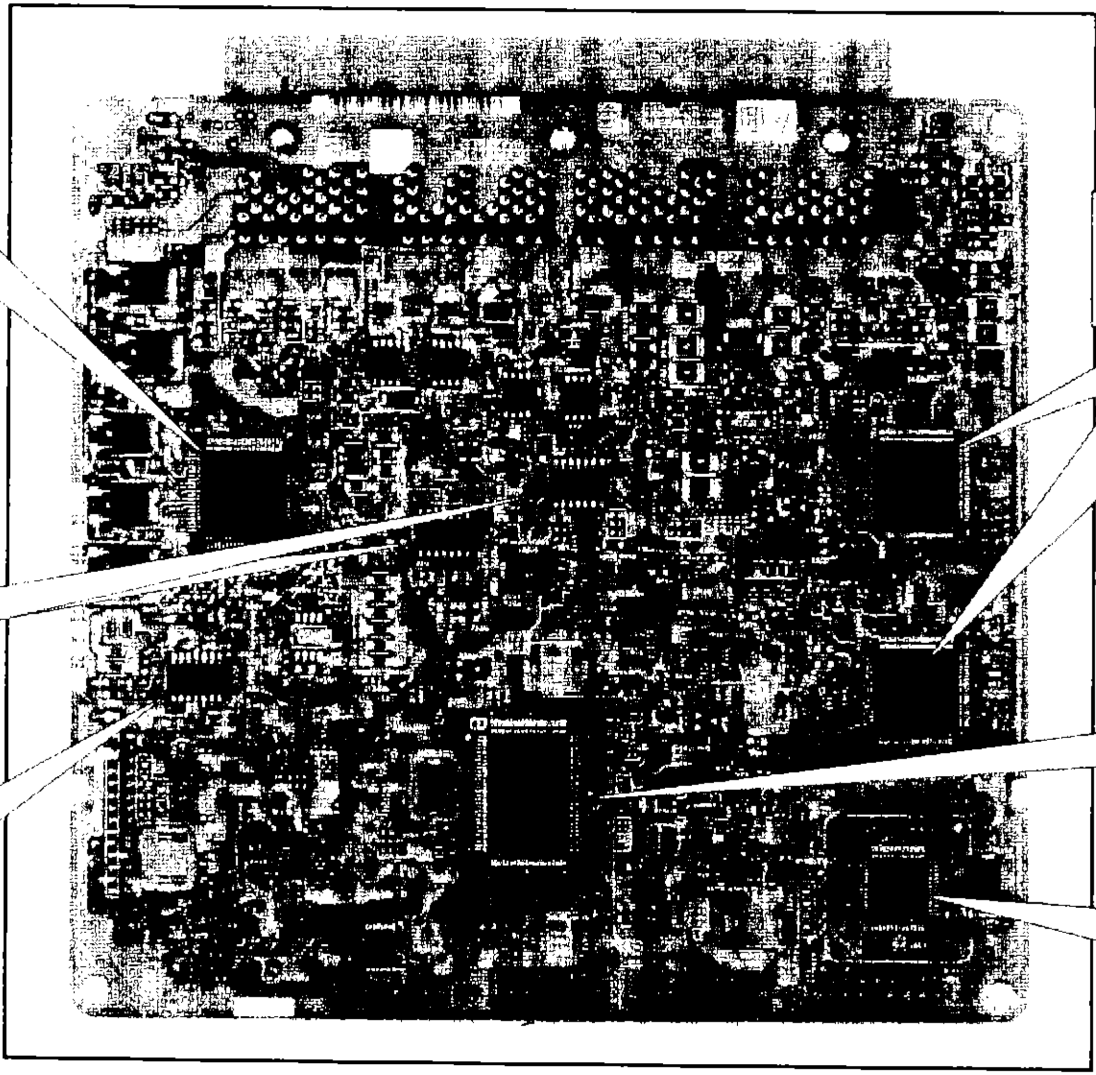
Toyota Prius:
HVECU – Side 2



#TB9298, #M30800, AU6802N1 seem to be working together and are duplicated.

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Inverter / Converter Unit (ICU)

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Summary: Inverter/Converter Unit

The Inverter/Converter Unit (ICU) is the ringmaster of all of the electrical conversion in the Prius, managing power from, between, and to the Motor/Generator units and battery. The two motor/generator units of the hybrid - MG1 and MG2 – each have somewhat different roles. MG1 recharges the high-voltage (~200V) NiMH battery pack located in the rear of the car and also applies direct power to drive the second MG2 assembly. MG1 additionally serves as the electric motor used to start the gas engine portion of the power train. MG2 is the primary electric drive motor when energized and under regenerative braking serves as the power generator where it is reversed in function. Both are permanent-magnet 3-phase devices, providing torque when driven by AC power or AC output when rotated from outside sources (either the gas engine or the wheel rotation during braking).

To create the 3-phase power for the motors, the DC battery source must be first stepped from 200V to 500V DC in a Boost Converter. A bank of insulated-gate bipolar transistors (IGBTs) with parallel diodes is mounted in bare-die form to a thermal plate with connection to a first ICU control board by way of feed connectors and ultra-heavy-gauge aluminum wedge bonds for power interconnect.

With a boosted DC voltage available, the Inverter is responsible for delivering the 3-phase power needed in the MG1 and MG2 assemblies when they are used as motors. Like the Boost Converter, IGBTs are used for power modulation in the Inverter and again the dedicated assembly plate supporting unpackaged transistor slices is used with similar interconnect to the controller board shared with the Boost Converter. The entire transistor / diode array assembly used by the Boost Converter and Inverter is encapsulated in a gooey sea of protective silicone gel. Four of the six legs of the Inverter have small current monitor assemblies present to keep tabs on power delivery to/from MG1 and MG2.

This same power semiconductor plate of the Inverter supports a set of diodes, again mounted as bare chips with one diode parallel to each of the IGBTs. These diodes are used under regenerative braking to rectify the AC output of the MG1/MG2 assemblies such that after filtering and regulation (using the boost converter circuit in reverse), energy recovered re-supplies the high-voltage battery pack

The Prius also uses an electric A/C compressor motor so that cabin cooling is maintained even when running in electric mode only. A second DC-AC inverter for powering the electric A/C compressor from the HV battery pack is used, with circuits located on a second ICU controller circuit board ringed with TO-packaged IGBTs. The A/C Inverter IGBT packages are bolted to one face of the substantial heat-sinking enclosure of the ICU. More on that shortly.

Lastly, since the Prius still needs a conventional electrical system to operate instrumentation, cabin lighting, etc., the ICU also supports step-down conversion from the 200V NiMH battery to the 12V subsystem where a conventional lead-acid battery is used. Circuits for the DC-DC converter share space on the same circuit board which is believed to be home to the A/C Compressor Inverter and TO-packaged devices are again bolted to the cooling plate of the overall ICU assembly.

The Boost Converter, the MG1/MG2 Inverter, DC-DC converter, and A/C Compressor Inverter all operate under the direction of and communicate with the HVECU discussed in the previous section of this report.

With the large currents involved throughout the ICU, cooling of power semiconductor devices is paramount. The two sets of power components – both bare direct-mount slices and the TO-packaged parts – are mounted back to back on the metal case of the ICU. Heat transfer is by way of a dedicated liquid cooling loop which runs through the ICU casing and is shared with the two MG assemblies.

Semiconductor content is critical in the ICU but with the exception of a control 32-bit CPU from Renesas (#HD6437049), IC content is mostly switcher and inverter control components. An NEC #uPC1099 Switching Regulator Controller and NEC #uPC494 Inverter Controller join with Toyota-custom power control devices and a number of transistor drivers for the implementing active circuits. Toshiba GT30J324 and Renesas 2SK1517 N-Ch MOSFETs comprise the array of TO-packaged transistors and Toyota-custom IGBTs/diodes are used on the bare-chip power semiconductor plate referenced earlier. Inductors, transformers, filter capacitors and a host of other passives complete the component set used in this impressive example of power engineering.

Much as the airflow, injectors, spark, and valves are the controlled aspects of the gas engine, the array of the DC-AC, AC-DC, and DC-DC converters are the managed elements of the electric drive train. Batteries and motors serve as rough parallels to the gas and mechanical pistons of the engine, and by teaming through the ECM and HVECU the two systems create an overall fuel-efficient source of power to get you down the road.

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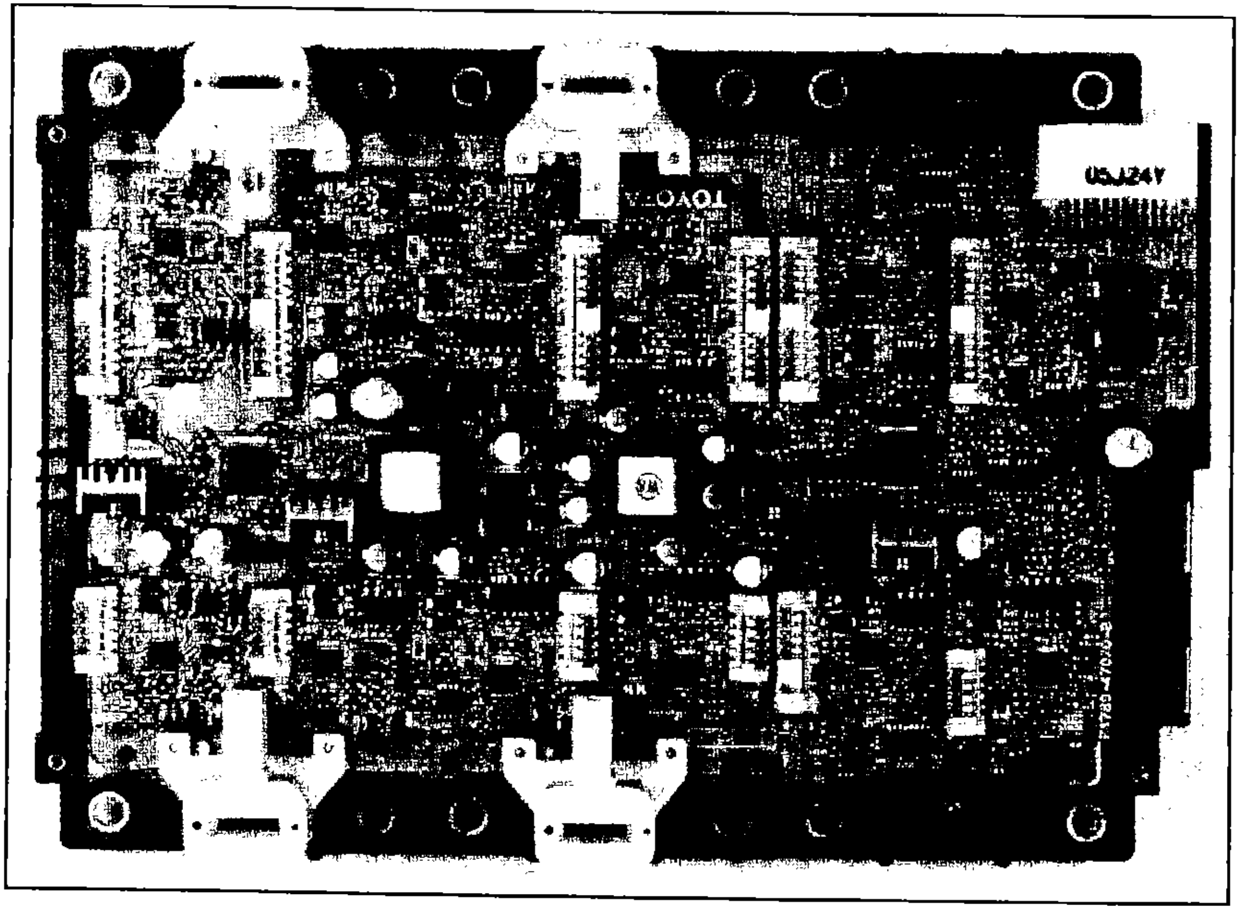
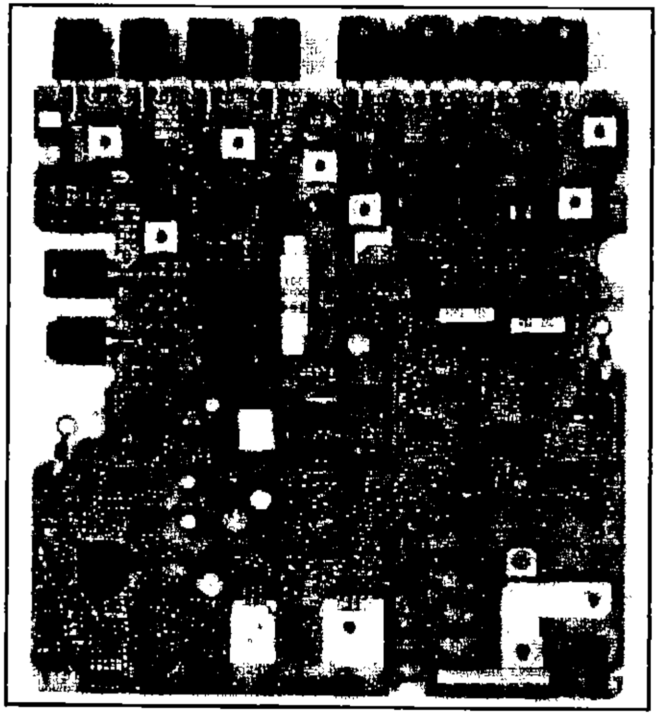
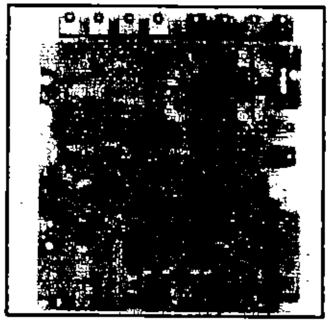
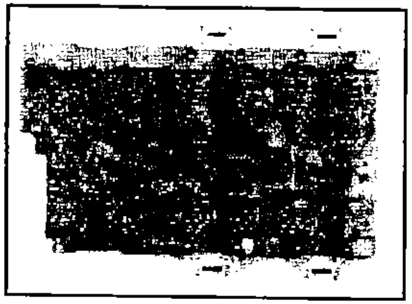
Toyota Prius: *Inverter/Converter Unit (ICU)*









Both boards primarily populated on one side.

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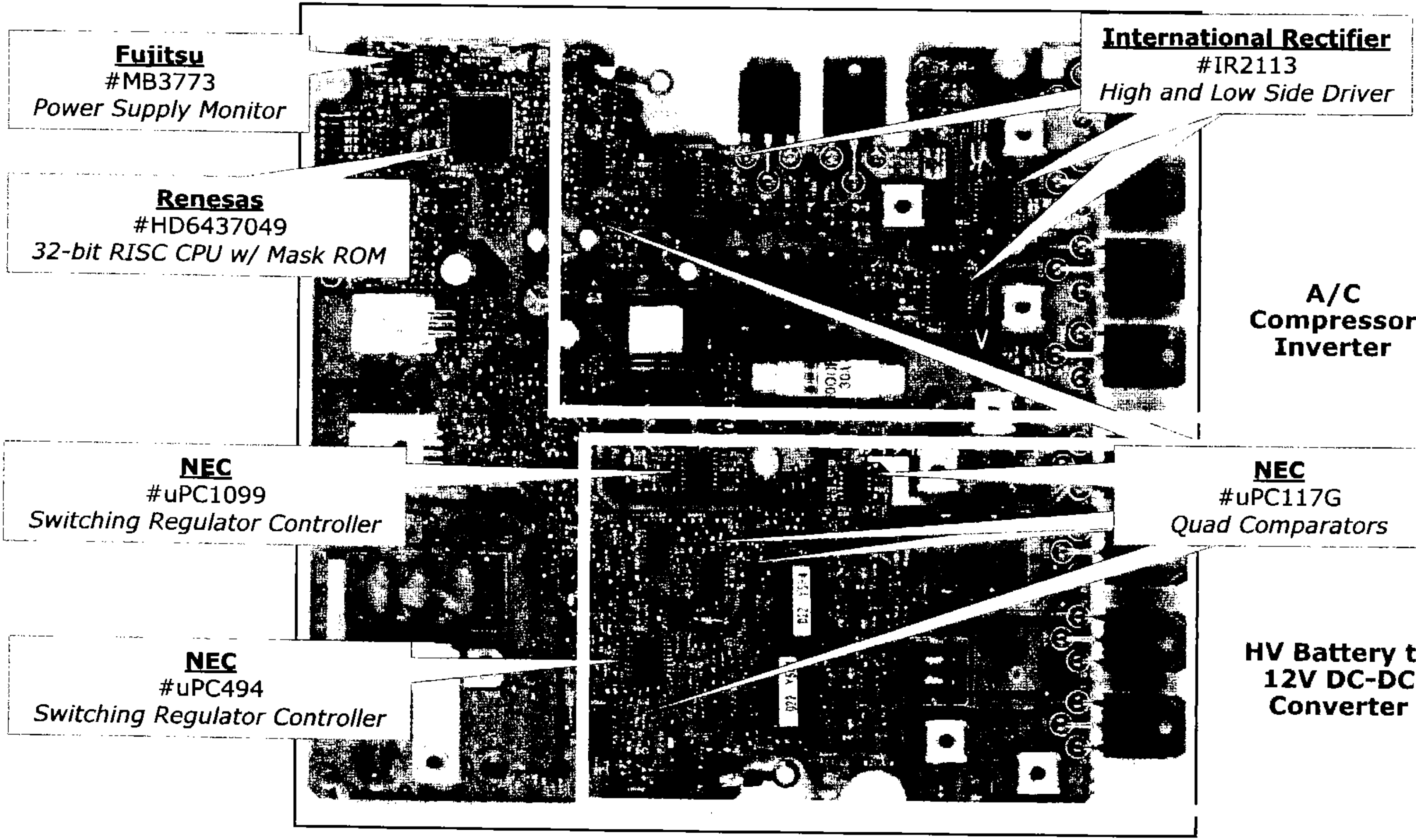
Toyota Prius:
Inverter/Converter Unit (ICU)



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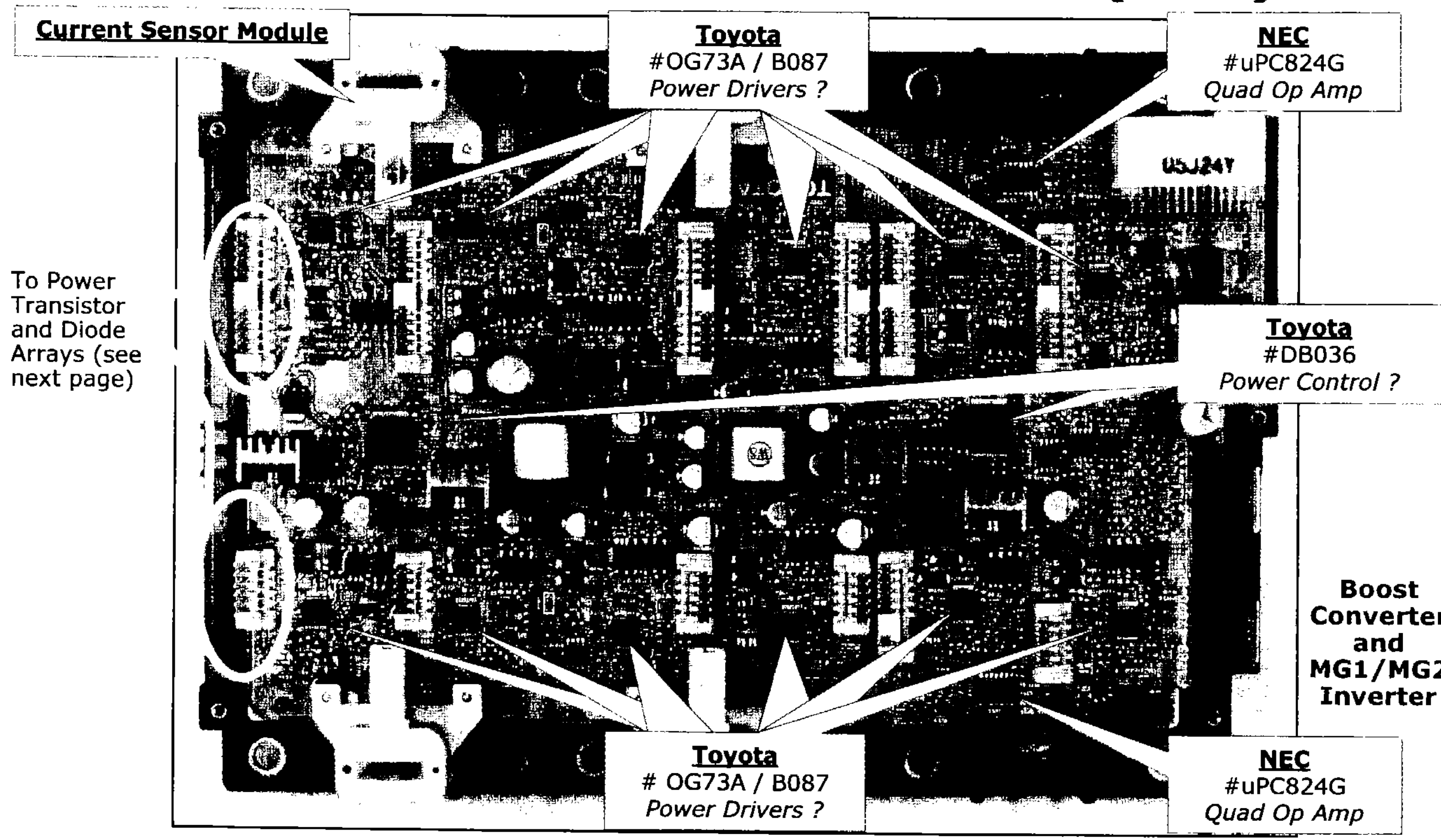
Toyota Prius:
Inverter/Converter Unit (ICU)



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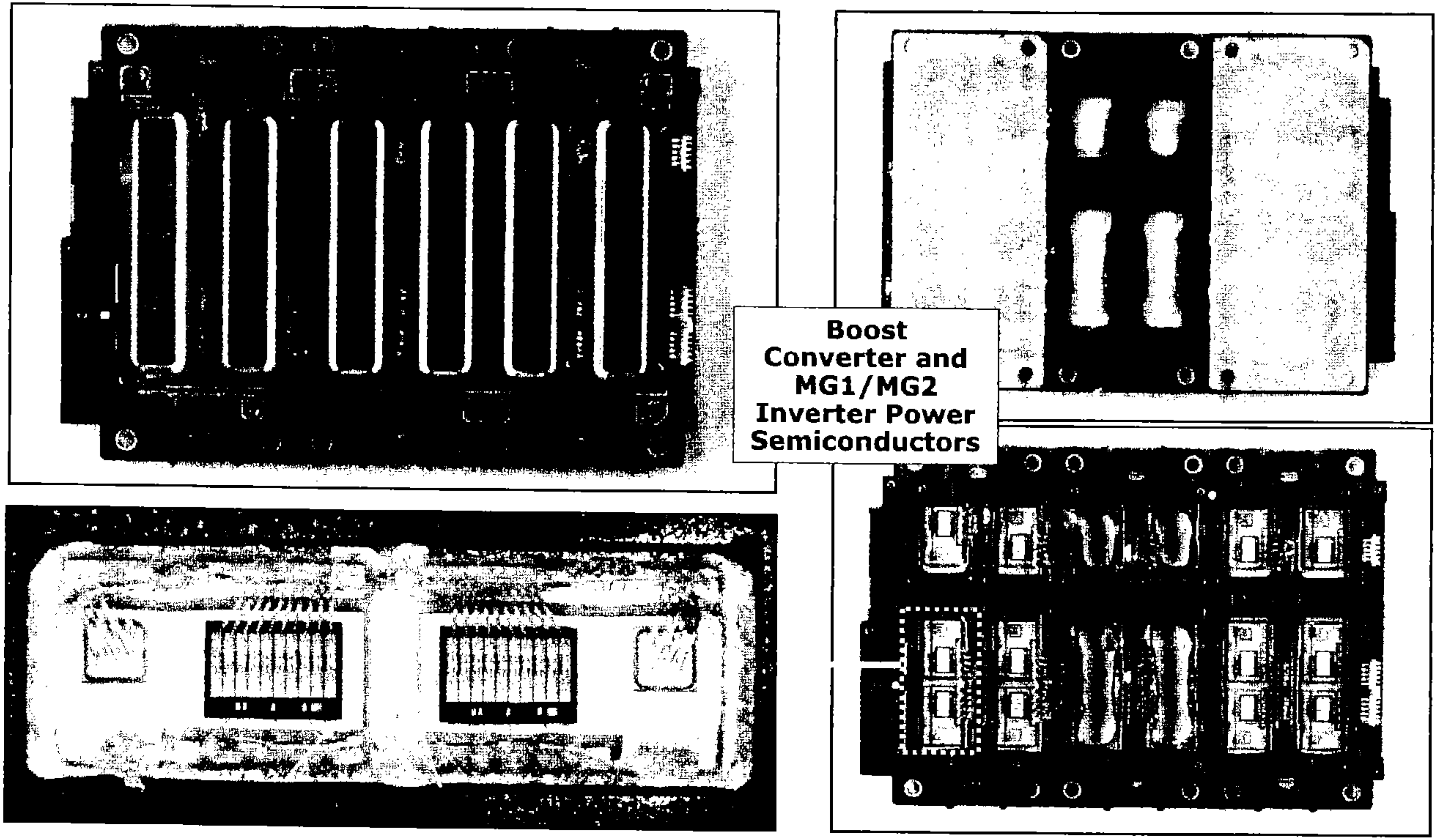
Toyota Prius:
Inverter/Converter Unit (ICU)



Massive drive transistors and rectifier diodes.

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Skid Control Module (SCM)

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Summary: Skid Control

The Prius' Skid Control Module (SCM) is a busy place in trying to control and correct a number of traction loss issues possible while driving. Working in concert with the Prius' Brake Control system, which drives the hydraulic friction braking and attempts to optimize use of regenerative braking as a fuel-saving measure, the SCM provides the smarts to tell each wheel exactly what to do when. Additionally, the SCM communicates closely with the drive train control electronics to modulate delivered power. Primary inputs to the SCM include the individual wheel-speed sensors, and the hydraulic pressure at the wheels' brake cylinder. Yaw, deceleration rate, and steering angle sensors are also inputs to the SCM used for tackling more complex vehicle stability control tasks.

Most of us have experienced the simplest case of traction control when we get a little overzealous with the accelerator on a slick road. While lighting up a set of tires may be fun, it's rarely safe and never an optimal way to deliver power to the pavement. Ask any drag racer and they'll tell you that minimizing wheel spin from the line and getting hooked-up is perhaps the biggest challenge of the craft. While the Prius powerplant pales in comparison to a 7000HP blown engine of a top-fuel drag racer, a wet or oily road is sometimes all it takes to lose traction from a stop, even with modest hybrid drivetrain power. The SCM here need only compare the rotation speed of the front (drive) wheels with that of the rear (undriven) wheels to detect simple wheel spin and back off on applied power to achieve front/rear wheel speed coherence.

Another task for the SCM is dealing with – and preventing – wheel lockup during panic stops. Anti-lock Braking Systems (ABS) are an almost universal standard on cars these days and the SCM adds ABS chores to its list. Working somewhat in opposite to the suppression of wheelspin on starts, the SCM here again monitors wheel speed to be sure each is hauling it down to a stop at the same rate. As soon as the SCM detects a wheel (or wheels) locking up, it instructs the Brake Control system to suspend further application of braking force whether by regenerative or hydraulic means, to minimize skid and maximize braking effectiveness. As with starting, the best stops occur when the tire maintains traction. Having narrowly avoided a deer which bounded out in front of my own car recently, I certainly came to appreciate ABS a bit further. A badly-bent car, or worse, would have been a certainty if not for great brakes and great automatic brake modulation.

Overall traction and stability control are the last elements of the SCM's function. Understeer or oversteer, which result in the car "pushing" through an intended turn or back-end "spin-out" respectively, are usually not a good thing and here again the SCM comes into play. By monitoring steering wheel angle, relative wheel speeds, yaw, and possibly lateral g-forces, the SCM can detect when either front wheel traction loss (understeer) or rear-wheel traction loss (oversteer) is imminent during turns. Again, the SCM works with the braking system to carefully direct applied braking forces at each of the four wheels to try and keep things under control.

Implementation of the SCM is conservative, as is the case of most mission-critical electronics we found in our Prius teardown. A meaty cast housing in the cabin and under the dash holds a single printed circuit board populated with peripherally-leaded IC device packages and spacious component layout. As shown in the picture, the SCM exhibits central symmetry, corresponding I suspect to the safety-minded control split of [front-right + left-rear] and [front-left + right rear] wheels. By implementing redundancy in this way, a partial failure still leaves one front wheel and one back wheel available for a SCM-driven controlled stop.

Analog circuits are key to the SCM implementation as input signal conditioning and output braking actuator drive are inherently non-digital tasks. The computational brains behind the SCM come from a Toyota-branded Toshiba #TMP1984FDFG 32-bit Microprocessor and a Mitsubishi #M30620 16-bit Microprocessor, the latter showing maskworks with a 1995 copyright date. Again, conservative design seems to be the principle. Beyond the number crunching however, Toyota turned to custom devices for the mixed signal interfaces. A Toyota #DA023 and Toyota #DA034 are each analog control or conditioning devices based on a peek at the bare chip. No merchant-market foundry markings were seen on the die but there was a nice little Toyota logo located next to the part number on both chips.

While the backside of the circuit board is mostly void of components, the large control currents within the analog parts require attention to thermal management. The #DA023 and #DA034 chips, replicated on left and right side, all have a thermal pad on the SCM board reverse side which carries heat away from the chips and makes contact into the SCM casing for keeping things cool.

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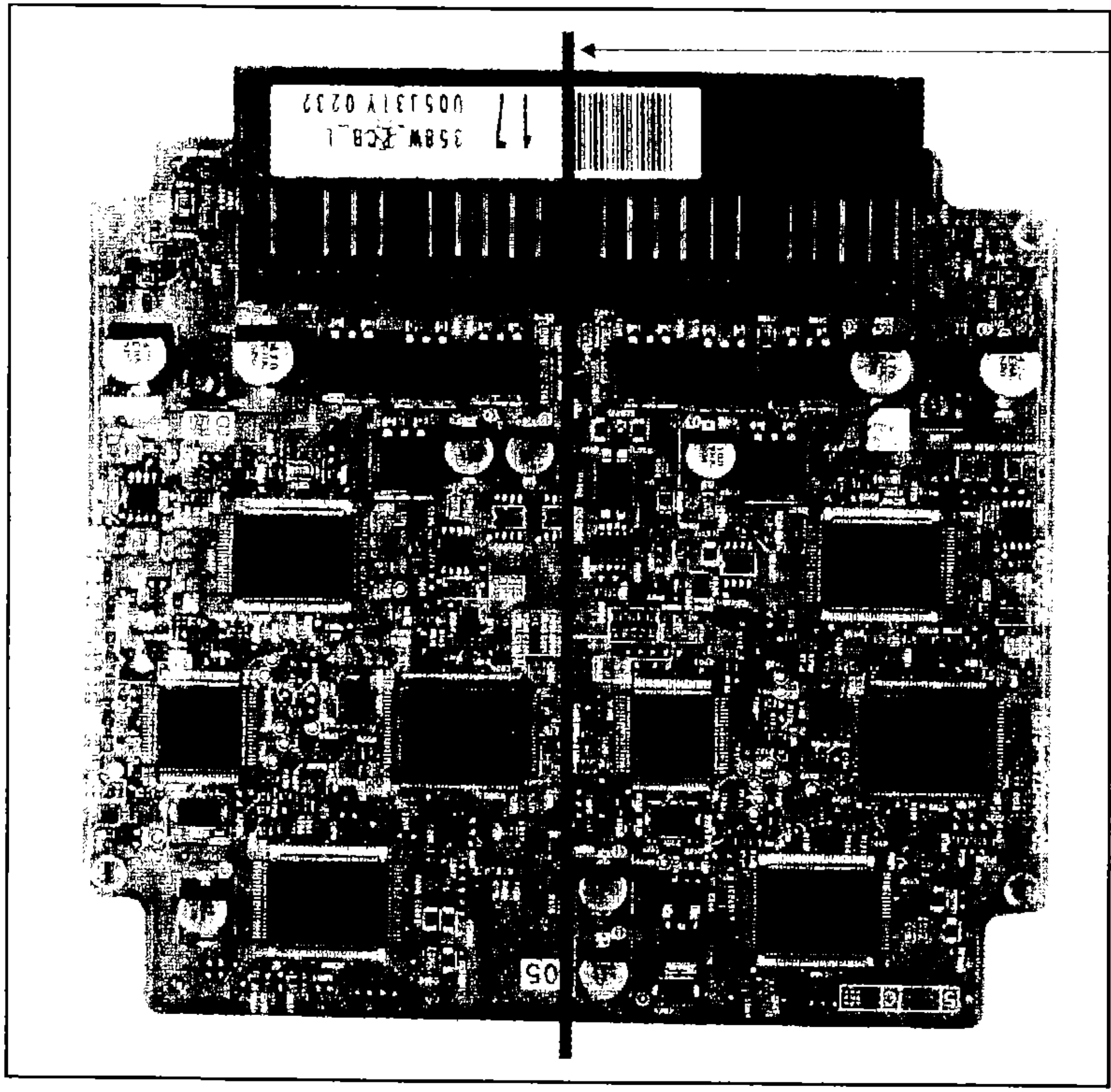
Toyota Prius:
Skid Control Module (SCM) Side 1/2



Note symmetry / duplication about red center line

Thermal Pad to SCM Casing